

REFLECTION SUPPRESSION FOR AN OPTICAL FIBER

CROSS REFERENCE TO RELATED APPLICATIONS

5 This application claims the benefit of priority to U.S. Provisional Application Serial Number 60/418,271 entitled "Method of Providing Low Cost Termination of an Unused Fiber Optic Strand" filed October 15, 2002. The subject matter of U.S. Provisional Application Serial Number 60/418,271 is hereby fully incorporated herein by reference.

10 This application is related to U.S. Non-Provisional Application Serial Number 10/045,439, entitled "Cable Splice Enclosure and Components," filed November 7, 2001. The subject matter of U.S. Non-Provisional Application 10/045,439 is hereby fully incorporated herein by reference.

FIELD OF THE INVENTION

15 The present invention relates to optical fibers and more particularly to managing internally reflected light in fiber optic terminations.

BACKGROUND OF THE INVENTION

20 Optical fiber is useful in communication networks to transmit digital and analog information via modulated optical signals. In a typical optical network, an optical fiber receives source light from a semiconductor laser, such as a vertical cavity surface emitting laser ("VCSEL"), a Fabry-Perot laser, or a distributed feedback laser ("DFB"). The optical fiber guides the light to an optical detector, which converts optical signals into corresponding electrical signals. Communications
25 equipment processes the electrical signals and decodes the information.

One type of communications equipment that converts optical signals into electrical signals is an optical detector. Optical detectors typically respond to light over a dynamic range. That is, over a range of intensities, most optical detectors

produce an electrical signal that linearly corresponds to the intensity of the light that is incident upon the optical detector. If the intensity of the optical signal that is incident upon the optical detector is higher than its dynamic range, the optical detector's performance can suffer. Consequently, assorted conventional devices are available to manage power in an optical network and keep the intensity of the optical signal within an optical detector's dynamic range.

In order to manage power, an optical network can include an optical attenuator positioned in the optical path between an optical source and an optical detector. So deployed, an optical attenuator can reduce the intensity of an optical signal and place it within the dynamic range of an optical detector. That is, conventional optical attenuators generally are power management devices that adjust the strength of an optical signal to optimize an optical detector's response to the optical signal. The conventional art includes numerous types of optical attenuators specific to this purpose. One type of conventional attenuator includes a small-diameter spool around which optical fiber is wrapped. The degree of attenuation is a function of the number of turns of optical fiber on the spool.

While attenuators find conventional utility for managing optical power, other conventional devices are generally used to address optical reflections in an optical network. In point-to-multipoint optical networks, a single light source is optically coupled to multiple fiber optic branches. At any time, some of the branches may be in service, actively transmitting optical signals to a destination, such as an optical detector at a subscriber premises. At the same time, other branches may be spares, held in reserve for network expansion. That is, the typical optical network includes active optical fibers transmitting information from a source to an optical detector and other reserve optical fibers that propagate or carry optical signals to a dead end. In other words, the reserve optical fibers are openly terminated, or are commonly said to be "unterminated." The reserve optical fibers are often optically coupled on one end to a source such as another active optical fiber and remain open on another end. In

this network configuration, light can propagate in an optical fiber with an open end face and, when incident on the end face, internally reflect off the open end face. This reflected light can then back propagate in the optical fiber and can interfere with network performance. Such stray light reflections from openly terminated optical
5 fibers in an optical network can cause performance problems.

Specifically, stray reflections from openly terminated optical fibers can impair the performance of an optical communications link by interfering with an optical detector, for example. When a stray reflection propagates in an optical fiber at the same time with another optical signal, an optical detector can confuse the two optical
10 signals. That is, when an optical network concurrently transmits a reflected optical signal and an optical signal supporting desired communication information to an optical detector, the signal-to-noise ratio of the network can suffer.

Stray reflections can also impair the performance of a semiconductor laser. When light reflects off an end face of an optical fiber and back into a semiconductor
15 laser, the back reflected light can interference with the laser's operation. For example, the back reflected light can destabilize the laser's lasing cavity.

An open end face of an optical fiber can internally reflect approximately four percent of the forward propagating light that is incident upon it. A number of conventional approaches have been taken to address such fiber optic back reflections.
20 Isolators are optical devices that suppress back reflections by allowing light to flow in one direction but not in the other. Isolators are often coupled to high performance lasers and generally are considered too expensive for routine fiber optic applications.

Another conventional approach includes adapting the end face of an optical fiber to either minimize the intensity of a back reflection or to prevent back reflected
25 light from back propagating in an optical fiber. Coating the end face with an antireflective film or patterning it with microstructures can minimize the intensity of back reflected light. Cleaving an optical fiber at an angle can produce an end face that deflects light away from the core of an optical fiber so that the optical fiber does

not significantly back propagate internal reflections. Implementing these approaches can be cumbersome or expensive, particularly under field conditions.

Another conventional approach includes permanently deforming an optical fiber, for example heating it to diffuse its core into its cladding or by forming a permanent kink in it. These processes typically require special equipment and are irreversible.

Yet another approach includes tying an optical fiber into a knot near an end face of the optical fiber. The knot attenuates the light that is propagating in the optical fiber towards the end face. Although the knot approach is generally convenient and can be implemented without special equipment, it has significant shortcomings. Since the distortion of the optical fiber in the knot is generally uncontrolled, the knot may impose significant and uncontrolled mechanical stress on the optical fiber. Such stress can shorten the life of the optical fiber or cause it to fracture. If a technician unties the knot and couples the optical fiber to an optical detector, the formerly-knotted section of optical fiber can prematurely fail. For example, the optical fiber can break without warning several years after the technician coupled it to an optical detector. Stresses associated with the knot can also cause an optical fiber to catastrophically fracture while it is knotted, for example before it is coupled to an optical detector. If the knotted optical fiber catastrophically fractures in the field resulting in a shatter rather than a clean break, the fracture can induce back reflections. Stresses can also induce micro fractures that cause back reflections, even without catastrophic failure of the optical fiber. If a technician does not tie the knot tight enough, sufficient light may propagate through the knotted section of optical fiber to impair network performance. Furthermore, the possibility exists for vibrations and cyclic heating and cooling to loosen the knot or cause it to come untied.

Another problem with the knotted-fiber approach is that light generally exits the core of the optical fiber over a very short length of optical fiber. For applications

involving high-power lasers, for example pump lasers and cutting lasers, the power density of the exiting light in this short section can be high. Over time, the potential exists for such power density to damage the optical fiber's coating or sheathing.

What is needed is a capability for managing back reflected light in an optical system so an end face of an optical fiber does not produce internal reflections that impair the performance of the system. This capability should be predictably reliable and should be conveniently implemented with minimal equipment. Such a capability would facilitate optical networks in cost-sensitive applications, such as fiber-to-the-home.

SUMMARY OF THE INVENTION

The present invention can include managing internal reflections in an optical fiber. An optical fiber can include an optical core surrounded by a cladding. To guide a wave of light along the length of the optical fiber, the core can have a higher refractive index than the cladding. One end of the optical fiber can receive light from a source such as an optical splitter, a semiconductor laser, or another optical fiber. On the opposite end, the optical fiber can have an end face, such as an exposed end face. Light can propagate from the source end to the end face. The end face can internally reflect light, causing it propagate back towards the source end. The present invention can suppress this back reflected light by attenuating light propagating in the optical fiber.

In one aspect of the present invention, a coil in an optical fiber formed with a spool near an end face can suppress internal reflections from the end face by attenuating light propagating to and from the end face. The radius of the spool and corresponding coil of optical fiber can be small enough to impair the core and cladding's ability to guide light. A fraction of the light propagating through the coil formed around the spool can leak out of the core and into the cladding, where it can dissipate and/or be absorbed. The spool can support a number of loops of optical

fiber. The fraction of light leaked from the optical fiber can increase as the radius of the spool and corresponding loops decreases and the number of loops supported on the spool increases. The radius of the spool can be chosen small enough and the number of loops of optical fiber on the spool can be chosen large enough to provide a level of attenuation that effectively suppresses end face reflections of the optical fiber. The level of attenuation in the open end optical fiber can be sufficient to meet a requirement such as a return loss specification in an optical networking application.

In another aspect of the present invention, the radius of the spool and the corresponding coil can be sufficiently large to control mechanical stress in the optical fiber. Controlling mechanical stress can provide a predicted reliability and/or lifetime for the optical fiber. Forming the coil around a spool can control the radius. The spool can include a restraint, such as an elastic slot, that holds an optical fiber around the spool until a user releases the optical fiber, straightens out the coil, and places the optical fiber into service.

In another aspect of the present invention, an optical fiber with internal reflection suppression can be a component in an optical system, such as a fiber optic communication link. The optical system can include an enclosure that contains the optical fiber, a spool that controls a coil radius, and an optical splitter coupled to the optical fiber. A drop optical fiber, coupled to the optical splitter, can lead out of the enclosure to an optical detector, such as an information receiver at a customer premises. A distribution optical fiber, also coupled to the splitter, can lead into the enclosure from a laser, such as an information transmitter.

The discussion of managing reflections presented in this summary is for illustrative purposes only. Various aspects of the present invention may be more clearly understood and appreciated from a review of the following detailed description of the disclosed embodiments and by reference to the drawings and claims.

BRIEF DESCRIPTIONS OF THE DRAWINGS

Figure 1 illustrates a perspective view of an optical fiber coiled around a termination attenuation spool according to one exemplary embodiment of the present invention.

5 Figure 2A illustrates an end-on cross section view of an optical fiber according to one exemplary embodiment of the present invention.

Figure 2B illustrates a longitudinal cross section view of an optical fiber according to one exemplary embodiment of the present invention.

10 Figure 3A illustrates an overhead view of a termination attenuation spool according to one exemplary embodiment of the present invention.

Figure 3B illustrates a cross section side view of a termination attenuation spool according to one exemplary embodiment of the present invention.

Figure 3C illustrates a side view of termination attenuation spool with an optical fiber according to one exemplary embodiment of the present invention.

15 Figure 3D illustrates a detail view of optical fiber wedged in a termination attenuation spool according to one exemplary embodiment of the present invention.

Figure 3E illustrates a detail view of a plurality of loops of optical fiber wedged in a termination attenuation spool according to one exemplary embodiment of the present invention.

20 Figure 3F illustrates a cross section cutaway view of a termination attenuation spool with a shoulder according to one exemplary embodiment of the present invention.

25 Figure 3G illustrates a detail view of a plurality of loops of optical fiber formed around a termination attenuation spool with a shoulder according to one exemplary embodiment of the present invention.

Figure 4 illustrates a cross sectional view an optical fiber formed into an attenuation loop according to one exemplary embodiment of the present invention.

Figures 5A and 5B illustrate optical attenuation data for an optical fiber coiled around a termination attenuation spool according to one exemplary embodiment of the present invention.

5 Figure 6 illustrates forward and back propagated optical signals in a fiber optic system that includes a pigtail optical fiber coupled to an optical splitter prior to coiling the optical fiber around a termination attenuation spool according to one embodiment of the present invention.

10 Figure 7 illustrates suppression of back reflected optical signals in a bidirectional fiber optic system that includes two transceivers and a pigtail optical fiber coiled around a termination attenuation spool according to one exemplary embodiment of the present invention.

Figure 8 illustrates a process for managing internal reflections in a fiber optic system according to an exemplary embodiment of the present invention.

15 Figure 9 illustrates a cross section of a fiber optic module including an enclosure and a termination attenuation spool for suppressing back reflection in an optical pigtail optical fiber according to one exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

20 Exemplary embodiments of the present invention support managing reflections in optical systems, such as suppressing internal reflections from an end face of an optical fiber. A termination attenuation spool attenuates light propagating forward in an optical fiber towards an exposed end face, and then attenuates the light internally reflected by the end face that back propagates in the optical fiber. Turning
25 now to the drawings, in which like numerals indicate like elements throughout the several figures, preferred and exemplary embodiments of the invention will be described in detail.

Figure 1 illustrates a perspective view of an optical fiber **110** coiled around a termination attenuation spool **100**. One end face **130** of the optical fiber **110** is exposed to the surrounding environment, which is typically a gaseous medium such as air. The termination attenuation spool **100** includes a top section **150** and a bottom section **160**. A cylindrical rod **140** joins the top section **150** and the bottom section **160**. The optical fiber **110** is coiled around the termination attenuation spool **100** between the top section **150** and the bottom section **160**. The termination attenuation spool **100** controls the radius of curvature of the loops **120** that make up the coil **120** to produce a desired level of attenuation without inducing excessive mechanical stress in the optical fiber **110**.

Light propagating forward in the optical fiber **110** from a source end **170** towards the exposed end face **130** propagates around the loops **120**. The radius of curvature of the loops **120** is sufficiently small to impair the optical fiber's ability to guide light. That is, the curvature impairs the optical fiber's capacity to function as an optical waveguide. As light propagates around the loops **120**, a portion of this light leaks out of the core of the optical fiber **110**. The remaining guided light propagates forward in the optical fiber **110** out of the optical fiber loops **120** and towards the exposed end face **130**. When this remaining light is incident upon the exposed end face **130**, a portion is internally reflected and propagated back towards the source end **170**. As the back propagated light propagates through the optical fiber loops **120**, a portion of this light also leaks out of the optical fiber core. The radius of curvature of the optical fiber loops **120** is large enough to control mechanical stress in the optical fiber **110** below a level that would damage the optical fiber **110** or otherwise compromise its reliability or intended lifetime.

By attenuating light in two passes, the termination attenuation spool **100** suppresses internal reflections from the exposed end face **130** to a desired level, such as that found in an engineering specification. If the optical fiber **110** is a component of a communication link, such as in an optical network, keeping back reflection

below a specified level allows the communication link to meet a performance criterion. For example, suppressing back reflection can facilitate a bit error rate specification in a digital optical communication network or a carrier to noise ratio specification in an analog optical communication network. For example, the engineering requirements of some optical networks specify that every optical element in the network provide a return loss of 35 decibels (“dB”) or better. Return loss for an optical element is ten times the common logarithm of the ratio of forward propagating optical power to back propagating optical power.

Figure 2A and 2B illustrate end-on and longitudinal views respectively of an exemplary optical fiber 110 that includes a core 210, a cladding 220, and a coating 230. For illustrative purposes, Figure 2 and subsequent figures somewhat exaggerate the dimensions of the core 210 and the coating 230 with respect to the cladding 220. The optical fiber 110 has a cladding 220 that axially surrounds a core 210. Both core 210 and cladding 220 are optical materials, such as glass, with the refractive index of the cladding 220 lower than the refractive index of the core 210. With this refractive index differential, light that is in the core 210 traveling along the longitudinal axis 240 of the optical fiber 110 remains in the core 210 and propagates along the length of the optical fiber 110. Thus, the optical fiber 110 functions as a waveguide for the light.

The refractive index differential between the core 210 and the cladding 220 is a factor in the relationship between bend radius and attenuation in a coiled section 120 of optical fiber. High refractive index differentials facilitate subjecting an optical fiber 110 to a tight bend with minimal attenuation. That is, for two tightly coiled optical fibers with unequal refractive index differentials, the coil with the larger differential typically generates less attenuation than the other coil.

As light propagates in an optical fiber 110 coiled around a termination attenuation spool 100, attenuation occurs primarily in the cladding 220. Light

coupled into the cladding **220** propagates in an evanescent mode and hence is attenuated exponentially with distance.

Figure 2B illustrates the optical fiber's exposed end face **130**, which is perpendicular to the longitudinal axis **240** of the optical fiber **110**. The end face **130** forms an optical interface **130** between the optical fiber **110** and a surrounding gaseous medium such as air. Light propagating forward in the optical fiber **110** towards the end face **130** is incident on the interface **130** between the optical fiber **110** and the surrounding medium as it emits from the optical fiber **110**. A portion of the incident light reflects off of the interface **130** and back into the optical fiber **110**.
For a glass optical fiber **110** exposed to an air medium, the interface **130** internally reflects approximately four percent of the incident light, under typical conditions. Stated another way, the intensity of the back propagated light is approximately 14 dB down from the intensity of the forward propagated light, or the exposed end face **130** generates approximately 14 dB of return loss. With the end face **130** perpendicular to the longitudinal axis **240** of the optical fiber **110**, the core **210** accepts the back reflected light, maintains it in a waveguided state, and back propagates it.

Forming the end face **130** at a non perpendicular angle (not shown) with respect to the longitudinal axis **240**, reduces the fraction of the forward propagating light that back propagates in the optical fiber **110** as a result of the glass-air interface **130**. Although angled end faces are more difficult to fabricate than perpendicular end faces **130**, the present invention can suppress back reflections from angled end faces as well as perpendicular end faces **130**.

The optical fiber **110** of Figures 2A and 2B includes a coating **230** that adheres to the cladding **220**. The coating **230** can be a polymer material that protects the glass portions **210**, **220** of the optical fiber **110** and promotes structural integrity.

The optical fiber **110** illustrated in Figures 1 - 2 is a step-index, glass single-mode optical fiber with a nominal numerical aperture ("NA") of 0.14 and a mode field diameter of approximately 10 microns. The outer diameters of the core **210**, the

cladding **220**, and the coating **230** are nominally 10, 125, and 250 microns respectively. Corning Incorporated, of Corning, NY, markets optical fiber under the registered trademark SMF-28 that is consistent with Figures 1 and 2.

The present invention is not limited to a single type of optical fiber or a single
5 fiber optic application. Embodiments of the present invention support and/or include a wide range of optical fibers that are known in the art. Optical fibers known in the art include: multimode optical fiber, all-silica optical fiber, gradient index optical fiber, step index optical fiber, matched cladding optical fiber, depressed cladding optical fiber, and silica-core plastic-clad optical fiber, among others. Some types of
10 optical fiber are highly tolerant to bending, by design. To provide a specified level of reflection suppression for such bending tolerant optical fibers, a termination attenuation spool **100** can have a smaller radius or a larger number of loops **120** than for SMF-28 optical fiber. Furthermore, a termination attenuation spool **100** may produce less attenuation for bending tolerant optical fibers than for ordinary single
15 mode optical fiber **110**.

Figures 3A – 3G illustrate embodiments of a termination attenuation spool **100** and further describe its construction and functionality with an optical fiber **110**. Figure 3A illustrates an overhead view of a termination attenuation spool **100** generally corresponding to the termination attenuation spool **100** illustrated in Figure
20 1. The top section **150** and bottom section **160** each have a diametrically-centered through hole. These holes accept a cylindrical rod **140** that joins the two sections **150**, **160** together. The cylindrical rod **140** can be formed of a rigid material such as plastic, metal, or ceramic. Suitable plastics include polycarbonate, acrylonitrile-butadiene-styrene (“ABS”), nylon, acetal, epoxy, and bakelite. Metals can be either
25 ferrous or non-ferrous, including steel, stainless steel, brass, and aluminum. The rod can also be made of elastomeric materials that are sufficiently stiff to provide structural support. Such elastomeric materials can include silicone, natural rubber, neoprene, and ethylene-propylene-diene-methylene (“EPDM”). All of these rod

materials are known to those skilled in the art and are available from a variety of commercial sources. The cylindrical rod 140 can be fabricated using a variety of process including molding, vacuum forming, extruding, and machining. The assembly 100 has a radius 310 that controls the radius of curvature of the loops 120 of optical fiber. Optical attenuation can be a function of the number of loops 120 and this radius 310, also referred to as the bend radius 310.

Figure 3B illustrates a cross section view of a termination attenuation spool 100 mounted on a base 320, such as the floor of an enclosure. The top and bottom sections 150, 160 each have the shape of a convex disk. These disks 150, 160 are mounted so that the convex contours face one another to form a tapered slot 330 or impinging region 330 to receive the optical fiber of the coil 120. The impinging region 330 can constrain the optical fiber 110 that a technician coils 110 around the termination attenuation spool 100.

In one embodiment of the present invention, the disks 150, 160 can be made of a pliable material, such as an elastomer, such as rubber or silicone, with a softness of approximately Shore A Durometer of 60-80. For example, the disks 150, 160 can be fabricated by machining rubber stock that has the approximate hardness of tire rubber. Alternatively, each disk 150, 160 can be molded of synthetic rubber or similar polymer. With the cylindrical rod 140 slightly larger than the through holes and the cylindrical rod 140 made of a rigid material, the disks 150, 160 can be press fit over the rod 140. Alternatively, the cylindrical rod 140 can be slightly undersized and the disks 150, 160 can be glued onto the rod 140. The cylindrical rod 140 can be attached to the base 320 using a variety of processes such as gluing, welding, and treading-tapping operations.

Figure 3C illustrates a side view of a termination attenuation spool 100 with optical fiber loops 120 coiled around the spool 100. The coiled optical fiber 120 is situated between the two convex disks 150, 160. The impinging region 330 between the two disks 150, 160 can hold the optical fiber loops 120 at a predetermined bend

radius 310. Coiling optical fiber 110 on the termination attenuation spool 100 so that the exposed end face 130 is close to the impinging region 330 protects the optical fiber 110 from handling damage. This arrangement facilitates a technician uncoiling the optical fiber 110 from around the termination attenuation spool 100 and deploying it for communication service.

Figure 3D illustrates a detail view of an optical fiber 110 wedged in an impinging region 330 of a termination attenuator spool 100. The elastic properties of the two disks 150, 160 enable the impinging region 330 to deform around the optical fiber 110 and capture it without causing damaging stress. When the optical fiber 110 is uncoiled from the termination attenuation spool 100, the impinging region 330 returns to its original contour and is ready to accept another optical fiber 110. As illustrated in Figure 3D, the exact position of an optical fiber 110 in the impinging region 330 varies according to the force with which the optical fiber 110 is wedged into the impinging region 330. Some variation in this position is tolerable while maintaining control over the radius of curvature 310 of coiled fiber. For a reasonable level of force, as might be applied by a technician in the field, the variation in this position can fall within a design window for the termination attenuation spool 100.

Figure 3E illustrates a detail view of a plurality of loops 120 of optical fiber wedged into an impinging region 330 of an attenuator spool 100. Each loop 120 occupies a slightly different position in the impinging region 330 and consequently has a slightly different radius of curvature 310. Averaging the position of each loop 120 yields an estimate of the radius of curvature 310 that is sufficiently precise to determine attenuation for most applications.

In one embodiment of the present invention, the cylindrical rod 140 that joins the two disks 150, 160 together establishes a minimum radius 310 of the coils 120 of optical fiber. Even if a technician coils the optical fiber 120 into the impinging region 330 with excessive force, the radius of curvature 310 of the coils does not fall below the radius of the cylindrical rod 140. Consequently, the radius of curvature 310 of the

coils **120** is greater than the radius of the cylindrical rod **140** and less than the radius of the disks **150, 160**. That is, the termination attenuation spool **100** controls the radius of curvature **310** of the loops **120** of optical fiber within a minimum and maximum value. These minimum and maximum levels can define stress and attenuation levels in the optical fiber **110**.

Figure 3F illustrates a cross section cutaway view of a termination attenuation spool **100** that has a shoulder **340** between the adjoining surfaces of two mated disks **150, 160**. The shoulder **340** defines the minimum radius **310** of each coil **120** of optical fiber that is wedged into the impinging region **330**. The shoulder **340**, which is a protrusion of the bottom disk **160**, mates into a cavity of the upper disk **150**. In one embodiment, the shapes of the disks **150** and **160** are reversed.

Figure 3G illustrates a detail view of a plurality of loops **120** of optical fiber coiled around a termination attenuation spool **100** and wedged into an impinging region **120** against a shoulder **340**. As illustrated in this figure, the shoulder **340** controls the radius of the loops **120** more precisely than a termination attenuation spool **100** with an impinging region **330** that does not have a shoulder **340** or similar structure.

Those skilled in the art recognize that the present invention is not limited to a spool **100**, which is one embodiment of a coiling device or a radius controlling device. Other coiling devices include, but are not limited to, mandrels, drums or any other round object of suitable diameter.

In an alternate embodiment (not shown) of the present invention, a cylindrical rod functions as a mandrel for the loops **120** of optical fiber. The radius of the mandrel defines the radius of curvature of the coil **120**. The outer surface of the mandrel, which contacts the coiled optical fiber **120**, can be soft so as to prevent damaging the optical fiber **120**, such as abrading or nicking it. The mandrel can be mounted on a base, for example perpendicular to the plane of the base. A technician

can coil optical fiber **110** around the mandrel. A detachable clip or a slot in the mandrel can hold the coiled optical fiber **120** on the mandrel.

In another alternate embodiment (not shown) of the present invention, the termination attenuation spool **100** is molded into a solid piece of synthetic rubber or similar polymer. In this embodiment, a cylindrical rod **140** is not needed to join two halves of the spool **100** together. A through hole in the center of the spool **100** can be formed in the molding process or by a post-molding drilling process. A bolt inserted in the through hole can be used to attach the termination attenuation spool **100** to a base **320** such as the housing of an enclosure.

Figure 4 illustrates a cross section view of a loop **120** of optical fiber within a coiled section **120** that attenuates light propagating therein. Figure 4 exaggerates the diameter of the optical fiber **110** with respect to the radius of curvature **310** of the coil **120** for illustrative purposes. Forward propagating light **410**, which is propagating away from the source end **170** towards the exposed end face **130**, enters the coil **120** and encounters a radius of curvature **310** that impairs the optical fiber's waveguiding capabilities. The curvature causes a portion **420** of the forward propagating light **410** to leak out of the core **210** and into the cladding **220**. Attenuation primarily takes place in the cladding **220**. Light coupled into the cladding **220** propagates in an evanescent mode and is attenuated exponentially with distance.

The coil **120** is optically symmetrical in that it provides approximately the same level of attenuation for forward propagating light **410** as it does for back propagating light **430**. A portion **440** of the back propagating light **430**, which propagates towards the source end **170** away from the exposed end face **130**, leaks out of the core **210** and into the cladding **220** where it is attenuated.

The phenomenon of a tight bend in an optical fiber **110** inducing attenuation has been described both in terms of ray theory and mode theory. In the context of ray optics, the light that leaks out of the core **210** and into the cladding **220** is sometimes referred to as "leaky rays" that refract out of the core **210** and into the cladding **220**.

In the context of mode theory of light propagation, which is often applied to single-mode optical fiber, the light that leaks out of the core **210** and into the cladding **220** is sometimes referred to as “leaky modes” that mode couple out of the core **210** and into the cladding **220**. Both ray theory and mode theory support intuitive and
5 mathematically rigorous treatments of the phenomenon. An intuitive explanation according to a mode theory follows immediately below with reference to Figure 4.

Single mode optical fiber **110** propagates light in a planar wavefront based on the refractive index profile of the optical fiber **110**. That is, the portion of the light field that is at the center **240** of the core **210** travels at the same speed as the portion
10 of the light field that is at the core-cladding interface **470**, **480**. A wavefront can be visualized as a plane of light traveling along the optical fiber’s longitudinal axis **240** with the plane perpendicular to that longitudinal axis **240**.

When the optical fiber **110** is formed into a coil **120** with a tight radius, there is an outer core-cladding interface **470** and an inner core-cladding interface **480**. The
15 inner core-cladding interface **480** is closer to the center **312** of the coil **120**, than the outer core-cladding interface **470**. Consequently, the circumference of the outer core-cladding interface **470** is significantly larger than the circumference of the inner core-cladding interface **480**. However, the light field follows both circumferences as it propagates through the loop **120**. To maintain the single mode optical fiber’s planar
20 wavefront, the portion of the light field at the outer core-cladding interface **470** needs to travel faster than the portion of the light field at the inner core-cladding interface **480**; however, the optical fiber’s materials do not provide for such a speed differential.

The curvature in the coil **120** may compress the optical materials at the inner
25 core-cladding interface **480** and stretch the optical materials at the outer core-cladding interface **470**. This material deformation may slightly increase the average refractive index at the inner core-cladding interface **480** and slightly decrease the average refractive index at the outer core cladding interface **470**. However, any such material

deformation that may exist does not sufficiently alter the refractive index profile to support the planar wavefront of single-mode propagation. That is, the portion of the wavefront that is at the outer core-cladding interface **470** does not travel significantly faster than the portion of the wavefront that is at the inner core-cladding interface **480**. Thus, for single-mode, waveguided propagation, a fraction of the light in the coil **120** needs to travel faster than the physics of the optical fiber **110** supports. This fraction of light couples out of the core **210** and into the cladding **220**. According to both theory and experimental results, attenuation increases as the bend radius **310** decreases and the number of loops **120** in a coil **120** increases.

Figure 5A and Figure 5B illustrate measured optical attenuation data for optical fiber **110** coiled under typical conditions. Figure 5A presents transmission loss data in graphical format **500** as a function of radius of curvature for 1550 nanometer (“nm”) light propagating in an optical fiber **110** coiled around a termination attenuation spool **100**. The dashed line, which is on the right, presents data for a quarter-loop, while the solid line, which is on the left, presents data for a full loop. Scaling these data according to the number of loops calculates total attenuation for a termination attenuation spool **100** with multiple loops.

For example, according to the data, a termination attenuation spool **100** having a radius of 8.9 millimeters (.35 inches) provides approximately .75 dB of attenuation per loop **120**. Since the termination attenuation spool **100** attenuates both forward and back propagated light, a coil **120** formed around this spool **100** provides 1.5 dB (.75 dB + .75 dB = 1.5 dB) of net attenuation per loop **120**. As described above, an exposed end face **130** generates approximately 14 dB of return loss. For a network that requires at least 35 dB of return loss, the termination attenuation spool **100** needs to provide at least 21 dB (35 dB - 14 dB = 21 dB) of total attenuation for the forward and backward propagating signal to meet the requirement. Thus, in this example of a spool **100** having a radius of 8.9 millimeters (.35 inches), the coil **120** should include at least 14 loops (1.5 dB x 14 = 21 dB) in order to meet the network’s

return loss requirement. The optical return loss is 21 dB (forward and backward passes around the attenuating spool) plus 14 dB corresponding to the reflection from an open-ended optical fiber. This results in a net optical return loss of 35 dB.

The graph 500 also illustrates that attenuation is highly non-linear with respect to radius of curvature. Below 12.7 millimeters (.5 inches), bending loss increases rapidly as the loop's radius 310 decreases. In one embodiment of the present invention, the coil 120 has a radius 310 less than 12.7 millimeters (.5 inches). In one embodiment of the present invention, the coil 120 has a radius 310 less than 9.5 millimeters (.375 inches). In one embodiment of the present invention, the coil 120 has a radius 310 less than 6.35 millimeters (.25 inches).

Physical stresses associated with bending an optical fiber 110 can shorten its predicted lifetime. Suppliers often proof test and grade optical fiber according to the stress that it can withstand. For a given application, higher proof test optical fiber typically has a longer expected lifetime than lower proof test optical fiber. Suppliers also may provide statistical data that predicts expected lifetime on the basis of the length of time that various bend radii 310 are applied to an optical fiber 110. The supplier may also predict expected lifetime on the basis of the length of the section of optical fiber that is subjected to various bend radii.

Corning Incorporated, of Corning, NY, makes such data available within the public domain for its optical fibers. For its SMF-28 optical fiber that has been proof tested to .69 GPa (100 kpsi), Corning provides statistical lifetime predictions for a one-meter length of optical fiber subjected to a various bend radii as follows. With a continuous 6-millimeter bend radius, the optical fiber stands a 1-in-10,000 chance of failing over a 20-to-40 year lifetime. With a 10-millimeter bend radius, the optical fiber stands a 1-in-100,000 chance of failing during the same lifetime. With a 16-millimeter bend radius, the optical fiber stands a 1-in-1,000,000 chance of failing during the same lifetime.

For optical fibers with less than one meter subjected to these bend radii, the probability of failure is lower than these predictions. If the termination attenuation spool **100** has less than one meter of coiled optical fiber **120**, the radius of the coil **120** can be smaller than the listed bend radii while maintaining the listed probabilities of failure and lifetimes.

In one embodiment of the present invention, the radius **310** of the coil **120** is at least 2 millimeters. In one embodiment of the present invention, the radius **310** of the coil **120** is at least 3 millimeters. In one embodiment of the present invention, the radius **310** of the coil **120** is at least 5 millimeters.

The supplier's reliability and lifetime data facilitates engineering a fiber optic system on the basis of reliability and lifetime requirements. For example, a submarine or an outer-space application may require more stringent reliability and lifetime standards than a fiber-to-the-home application.

Thus, the radius **310** of the termination attenuation spool **100** can be selected according to a reliability standard or a predicted lifetime for the optical fiber **110**. Based on this radius **310**, the number of loops **120** of optical fiber can be selected according to a desired level of return loss. The return loss can be defined on the basis of network performance, such as bit error rate or carrier-to-noise ratio. The return loss specification can be based on a requirement for the network that all components deployed in the network meet or exceed a return loss threshold.

Figure 5B is a table that illustrates attenuation per loop **120** at 1310 nm and 1550 nm for a termination attenuation spool **100** having a radius of 4.8 millimeters (3/16 inches). Based on these data, coiling an optical fiber **110** with six loops **120** around such a spool **100** provides 22.8 dB of return loss enhancement at 1310 nm. Added to 14 dB of inherent return loss from an exposed end face **130**, the termination attenuation spool **100** achieves a total return loss of 36.8 dB. This value meets the specification of a network that requires at least 35 dB of return loss.

Those skilled in the art can appreciate that the present invention supports optimizing the design parameters of a termination attenuation spool **100** to meet lifetime, reliability, and return loss requirements. For example, the termination attenuation spool **100** can be factor in determining reliability and lifetime for an optical communication system that includes optoelectronic components.

Figure 6 illustrates an exemplary optical network system **600** with a communication link between a laser **680** and a detector **690**. The system **600** further includes a pigtail optical fiber **110** and a termination attenuation spool **100** prior to coiling the pigtail optical fiber **110** onto the termination attenuation spool **100**. In this state, the pigtail optical fiber's exposed end face **130** generates an internal reflection that can impair the performance of the optical system **600**.

The system **600** includes a semiconductor laser **680** that launches source light **609** into a section of distribution optical fiber **605**, which couples the laser **680** to an optical network **600**, **608**. Either direct modulation of the laser **680** or external modulation of the light **609** emitted by the laser **680** modulates a signal onto the source light **609**. The signal **609** may be a digital signal or an analog signal or both. The communication link between the laser **680** and the detector **690** passes through a region **608** of the optical network **600**, **608** that can be coupled to other data links and optical networking devices that are not illustrated in Figure 6. Another section of distribution optical fiber **620** transmits the optical signal **609** out of this optical network region **608** and to an optical splitter **610**.

The optical splitter **610** receives the optical signal **609** from the distribution optical fiber **620** and feeds it to a plurality of optical ports **650** coupled to egress optical fibers **630**, **110**. The fiber optic splice tray **640** manages and protects the splitter **610** and its associated optical fibers **620**, **630**, **110**. Figure 6 illustrates two exemplary egress optical fibers **630**, **110** connected the splitter ports **650**. In a typical field application, the splitter **610** is a source for four, six, eight, sixteen, or more egress optical fibers **630**, **110**. In one embodiment of the present invention, the

optical splitter **610** is an optical combiner. In one embodiment of the present invention, the optical splitter **610** is an optical coupler. In one embodiment of the present invention, in addition to splitting optical signals, the optical splitter **610** is functional to combine optical signals.

5 One **630** of the two egress optical fibers **630**, **110** is a drop optical fiber **630** that carries a portion **618** of the optical signal light **609** to a semiconductor optical detector **690**. The semiconductor optical detector **690** receives the optical signal **618** and generates a corresponding electronic signal.

10 The other egress optical fiber **110** is a pigtail optical fiber **110** with an exposed end face **130**. Although not in service, the pigtail optical fiber **110** is optically active and carries an optical signal **410** from the optical splitter **610** that has similar optical power to the optical signal **618** in the drop optical fiber **630**.

15 The optical signal **410** from the optical splitter **610** propagates forward in the pigtail optical fiber **110** towards its exposed end face **130**. Back reflected light **430** from the exposed end face **130** propagates backwards towards the optical splitter **610**. The optical splitter **610** couples the back reflected light **430** from the optical pigtail **110** into the distribution optical fiber **620**. The distribution optical fiber **620** propagates this back reflected light **692** into a region **608** of the optical network **600**, **608** that can be coupled to a variety of other data links and optical networking
20 components (not illustrated). Here, the stray back reflected light **692** can interfere with the performance of such networking components and data links.

 If stray back reflected light **692** transmits in a data link along with an optical signal that supports desired communication information, the data link's detector can respond to the stray light **430** thereby degrading signal-to-noise ratio of that data link.
25 Also, back reflected light **692** propagating in the distribution optical fiber **620** can interact with the semiconductor laser **680** and add noise to its optical signal, thereby reducing the communication performance of the system **600**.

Figure 6 illustrates the pigtail optical fiber **110** in an uncoiled state. Coiling the pigtail optical fiber **110** around the termination attenuation spool **100** suppresses back reflections **410**, **692** and prevents them from degrading communication performance of the optical network **600**, **608**. When the pigtail optical fiber **110** is coiled around the termination attenuation spool **100**, the optical signals **410**, **430** propagating to and from the end face **130** are attenuated. Although a residual optical signal **692** remains after two attenuation passes around the termination attenuation spool, its intensity is weak. The intensity of the residual optical signal **430** that back propagates in the distribution optical fiber **620** is reduced to support communication performance of the optical networking system **600**.

Figure 7 illustrates a bi-directional fiber optic system **700** with a termination attenuation spool **100** to suppress reflections from a pigtail optical fiber **110**. An upstream transceiver **710** sends optical signals **702** to and receives optical signals **704** from a downstream transceiver **720** over a fiber optic link that includes a distribution optical fiber **620**, an optical splitter **610**, and a drop optical fiber **630**. The upstream transceiver **710** includes a laser **730** that launches optical signals **702** into the distribution optical fiber **620** and an optical detector **725** that receives optical signals **704** from the distribution optical fiber **620**.

The upstream laser **730** launches an optical signal **702** into the distribution optical fiber **620**, which propagates this downstream optical signal **702** in the downstream direction to an optical splitter **610**. The optical splitter **610** splits the downstream optical signal **702** between a drop optical fiber **630** and a pigtail optical fiber **110** with an exposed end face **130**. The drop optical fiber **630** receives a portion **706** of the downstream optical signal **702** from the optical splitter **610** and transmits this portion **706** to the downstream transceiver **720**. An optical detector **740** in the downstream transceiver **720** receives this downstream optical signal **706** and generates a corresponding electrical signal. Communication equipment (not shown) coupled to the downstream transceiver **720** typically processes information encoded

in the electronic signal and generates information for communication back to the upstream transceiver 710.

5 The laser 735 in the downstream optical transceiver 720 launches an upstream optical signal 708 into the drop optical fiber 630. The drop optical fiber 630 propagates the upstream optical signal 708 in the upstream direction to the optical splitter 610. The optical splitter 610 directs this upstream optical signal 704, 708 into the distribution optical fiber 620. The distribution optical fiber 620 propagates the upstream optical signal 704 to the upstream transceiver 710. The upstream transceiver's optical detector 725 receives the upstream optical signal 704 and
10 generates a corresponding electrical signal.

Bidirectional communication, in which a single optical fiber 620, 630 sends and receives optical signals, is particularly susceptible to unsuppressed reflections. Unsuppressed reflections can propagate along with the optical signals that support desired communication and interfere with a detector's performance in isolating the
15 desired communication signal. In other words, stray back reflections that are too strong diminish an optical detector's capacity to discriminate between a desired optical signal and those reflections.

As described above, the optical splitter 610 receives the downstream optical signal 702 from the laser 730 in the upstream transceiver 710 and splits it between a
20 drop optical fiber 630 and a pigtail optical fiber 110, as well as splitting the downstream optical signal 702 between any other ports on the optical splitter 610. The pigtail optical fiber 110 propagates its portion of this downstream optical signal 410 to a section of optical fiber coiled around a termination attenuation spool 100. The optical signal 410 is attenuated as it propagates around the termination
25 attenuation spool 100 towards the end face 130 of the pigtail optical fiber 110. The end face 130 back reflects a portion of this downstream optical signal 410. The pigtail optical fiber 110 captures the back reflected downstream optical signal 430 and propagates it in an upstream direction towards the optical splitter 610. As the

back reflected downstream optical signal **430** propagates upstream in the pigtail optical fiber **110** around the termination attenuation spool **100**, it is attenuated.

The two attenuating passes around the termination attenuation spool significantly reduce the optical power in the residual downstream optical signal **430** that is propagating upstream in the drop optical fiber **110** towards the optical splitter **610**. In one embodiment of the present invention, the optical power in this residual optical signal **430** is 35 dB below the optical power of the downstream optical signal that is coupled in the downstream direction out of the optical splitter **610** and into the pigtail optical fiber **110**.

The optical splitter **610** receives the residual back reflected downstream optical signal **430** and couples it into the distribution optical fiber **620**, which propagates it to the upstream transceiver **710**. The residual back reflected downstream optical signal **430** is coupled into the upstream transceiver's optical detector **725** along with the upstream optical signal **704** from the laser **735** in the downstream transceiver **720**. That is, two optical signals **430**, **704** are coupled into the upstream transceiver's detector **725**, one **704** that supports desired communication and one **430** with the potential to interfere with desired communication.

With the optical fiber pigtail **130** coiled around the termination attenuation spool **100**, the strength of the back reflection is suppressed to a level that reduces its capacity to interfere with desired communication. The portion **430** of the back reflection that reaches the upstream transceiver's detector **725** is weak. That is, suppressing back reflections from the exposed end face **130** improves the signal-to-noise ratio of the communication system **700**. Such signal-to-noise ratio performance can be a carrier-to-noise ratio for analog communication or a bit error rate for digital communication.

Figure 8 illustrates a process **800** for managing back reflections in a fiber optic system according to one embodiment of the present invention. Step **805** is the first step of Process **800**. In Step **805**, a light source such as a semiconductor laser

680 generates an optical signal. At Step 810, the semiconductor laser 680 launches the optical signal into the source end of an optical waveguide 620. At Step 815, the optical waveguide 620 propagates the optical signal towards an exposed end face 130 of an optical waveguide 110 that is opposite the source end. At Step 820, the optical
5 waveguide 620 propagates the optical signal into an enclosure (illustrated in Figure 8 and described below).

In Step 825, an optical splitter 610 in the enclosure splits the optical signal into a first and a second optical signal. At Step 830, an optical waveguide such as a drop optical fiber 630 propagates the first optical signal 410 out of the enclosure to an
10 optical detector 690. At Step 835, an optical waveguide 110 such as a pigtail optical fiber receives the second optical signal 410 from the splitter 610 and propagates it towards an exposed end face 130.

At Step 840, the optical waveguide 110 propagates the second optical signal 410 through a section 120 of optical waveguide 110 coiled around a termination
15 attenuation spool 100. At Step 845, the termination attenuation spool 100 attenuates the second optical signal 410 by leaking a portion 420 of it out of the core 210 of the optical waveguide 110. At Step 850, the exposed end face 130 back reflects the second optical signal 430. At Step 855, the optical waveguide 110 back propagates the second optical signal 430 through the section 120 of optical waveguide 110 coiled
20 around the termination attenuation spool 100. At Step 860, the termination attenuation spool 100 attenuates the back propagated optical signal 430 by leaking a portion 440 of it out of the core 210 of the optical waveguide 110.

Figure 9 illustrates a cross section of an exemplary opto-mechanical system 900 that includes an optical subsystem 600 mounted in an enclosure 910 for field
25 deployment according to one exemplary embodiment of the present invention. The optical system 600 generally corresponds the optical system 600 illustrated in Figure 7 and includes an optical fiber 620 that feeds an optical splitter 610, which is mounted in a receptacle or similar mount in the enclosure 910. The optical splitter 610 feeds a

drop optical fiber 630 and a pigtail optical fiber 110. The drop optical fiber 630 leads out of the enclosure 910 through a drop port 950. The illustrated enclosure 910 has eight exemplary drop ports 950. Other enclosure embodiments can include various numbers of drop ports 950. The pigtail optical fiber 110 is coiled in loops 120 around a termination attenuation spool 100 so that the end face 130 of the pigtail optical fiber 110 is internal to the enclosure 910 and exposed to the air or gaseous environment of the inside of the enclosure 910. The termination attenuation spool 100 mounts on the floor of the enclosure's housing 910. A fiber optic splice tray 640 or similar apparatus manages drop optical fibers 630 and pigtail optical fibers 110 inside the enclosure to promote organization and avoid handling stress.

The optical fiber 620 that feeds the optical splitter 610 is a distribution optical fiber 620 that is a component in a distribution cable 920. The distribution cable 920 enters the enclosure 910 through a cable port 925. The distribution cable 920 includes strength members 930 that prevent uncontrolled tensional stress from being transferred to the optical fiber 620. Strength members 930 can comprise one or more strands 930 of metal, fiberglass, Kevlar, or other flexible, low-stretch material. The cable port 925 can include a watertight seal (not shown) to prevent moisture from entering the enclosure 910. In one embodiment of the present invention, this seal is a hermetic seal. The enclosure 910 includes three cable ports 925 for distribution cables 920. This arrangement of cable ports 925 accommodates several configurations for mounting and using the system 900.

A cable strain-relief device 935, which is adjacent each cable port 925, holds the distribution cable 920 in place with respect to the housing 910. The cable strain-relief device 935 grasps the distribution cable 920 with a hose clamp or screw fastener arrangement or by glue, weld, or other attachment system. In operation, the cable strain-relief device 935 is coupled both to the housing structure 910 and to the distribution cable 920.

A strength-member strain relief device **940**, which is situated near each cable strain relief device **935**, grasps the distribution cable's strength members **930** with a mechanical clamp, glue, or other fastening system. The strength-member strain-relief device **940** is attached to the housing **910** with bolts or screws, or by gluing, welding,
5 or other methods. In operation, the strength-member strain-relief device **940** is coupled both to the housing structure **910** and to the distribution cable's strength members **930**.

The enclosure **910** includes a cover plate (not shown) that attaches to the housing **910** and seals the optical subsystem **600** of the system **900**. The housing **910**
10 can be constructed from a variety of materials such as metal or molded plastic. The housing also includes mounting brackets **960**. For field deployment, a technician can attach the system **900** to an overhead cable or a rigid structure such as a building wall using the mounting brackets **960**.

The diameter of the drop ports **950** is smaller than the diameter of the cable ports **925** since the drop optical fibers **630** are typically thinner than the distribution cables **920**. A drop strain-relief device **955**, which is adjacent each drop port **950**, grasps each drop optical fiber **630**. The drop strain-relief device **955** prevents stress on the portion of the drop optical fiber **630** that is external to the enclosure **910** from transferring to the optical splitter **610**. If a sheath, such as a hollow tube with
15 accompanying strength members, encases and protects each drop optical fiber **630**, the drop strain-relief device **955** can grasp the sheath or the strength members rather than the drop optical fiber **630** itself. The drop strain relief device **955** can be coupled to housing **910** with bolts or screws, or by gluing, welding, or other methods.
20

While Figure 9 illustrates a single drop optical fiber **630** and a single pigtail optical fiber **110** coupled to the optical splitter **610**, the present invention supports
25 managing numerous drop optical fibers **630** and pigtail optical fibers **110**. In one embodiment of the present invention, a single termination attenuation spool **100** manages multiple optical fibers **110**. In another embodiment of the present invention,

each spool **100** manages a single optical fiber **110**, and the enclosure **910** contains multiple spools **100**. A field technician can bring a spare pigtail optical fiber **110** into service by uncoiling it from the termination attenuation spool **100** and threading it through a port **950**. Alternatively, a field technician can fuse a long optical fiber to the pigtail optical fiber **110** and thread the lengthened optical fiber through the port **950**. Also, a field technician can remove a drop optical fiber **630** from service, pull it back through the port **950**, and coil it onto the termination attenuation spool **100**. The unused optical fiber pigtail **110** may have a connector (not shown) on it which may be connected at some future time to another optical fiber so that the pair functions as a drop optical fiber, similar to the illustrated drop optical fiber **630**.

As illustrated in Figure 7, in one embodiment of the present invention, the distribution optical fiber **620** receives light **702** from a source such as a semiconductor laser **725** and delivers this light **702** to an optical splitter **610**. The drop optical fiber **630** receives light **706** from the optical splitter **610** and delivers this light **706** to an optical detector **740**. In one embodiment of the present invention, the drop optical fiber **630** couples to an optical detector **740** at a specific physical location, such as a home or office building. To bring service to a new customer, a technician uncoils a spare pigtail optical fiber **110** from the termination attenuation spool **100** and couples the optical fiber **110**, either directly or through an intermediate optical fiber, to an optical detector **740** at the customer's premises.

One skilled in the art would appreciate that the present invention supports managing back reflections in optical fiber systems such as optical networks. In one embodiment, the present invention suppresses internal reflections from an exposed end face of an optical fiber that is optically active but is held in reserve for future service. Forming a coil of controlled radius adjacent an exposed end face of an optical fiber suppresses back reflections from that end face. The radius of the coil is small enough to impair the optical fiber's ability to maintain a waveguided state and large enough to control mechanical stress in the optical fiber coil.

A termination attenuation spool can suppress reflections by attenuating light in two passes. In the first pass, a fraction of the forward propagating light in the coil, which propagates towards the end face, leaks out of the optical fiber's core and does not reach the end face. The end face back reflects another fraction of the forward
5 propagating light that makes it through the coil and is incident upon the end face. In the second pass, the optical fiber captures a portion of the back reflected light and guides it back to the coil. As this light back propagates through the coil, a fraction leaks out of the optical fiber's core.

From the foregoing, it will be appreciated that the preferred embodiment of
10 the present invention overcomes the limitations of the prior art. From the description of the preferred embodiment, equivalents of the elements shown herein will suggest themselves to those skilled in the art, and ways of constructing other embodiments of the present invention will suggest themselves to practitioners of the art. Therefore, the scope of the present invention is to be limited only by the claims below.